

# Chemical composition of evolved stars in the open cluster IC 4651\*

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## ABSTRACT

We present an analysis of high-resolution spectra of three core-helium-burning ‘clump’ stars and two first ascent giants in the open cluster IC 4651. Atmospheric parameters ( $T_{\text{eff}}$ ,  $\log g$ ,  $v_t$ , and [Fe/H]) were determined in our previous study by Carretta et al. (2004). In this study we present abundances of C, N, O and up to 24 other chemical elements. Abundances of carbon were derived using the C<sub>2</sub> Swan (0,1) band head at 5635.5 Å. The wavelength interval 7980–8130 Å, with strong CN features, was analysed in order to determine nitrogen abundances and <sup>12</sup>C/<sup>13</sup>C isotope ratios. The oxygen abundances were determined from the [O I] line at 6300 Å. Compared with the Sun and other dwarf stars of the Galactic disk, mean abundances in the investigated clump stars suggest that carbon is depleted by about 0.3 dex, nitrogen is overabundant by about 0.2 dex and oxygen is close to solar. This has the effect of lowering the mean C/N ratio to  $1.36 \pm 0.11$ . The mean <sup>12</sup>C/<sup>13</sup>C ratios are lowered to  $16 \pm 2$ . Other investigated chemical elements have abundance ratios close to the solar ones.

**Key words:** stars: abundances – stars: atmospheres – stars: horizontal branch – open clusters and associations: individual: IC 4651.

## 1 INTRODUCTION

This work is continuing our efforts in studying evolutionary abundance alterations in evolved stars of open clusters (Tautvaišienė et al. 2000, 2005; Mikolaitis et al. 2010). Our main aim is to determine detailed elemental abundances of carbon, nitrogen and oxygen, and carbon isotope <sup>12</sup>C/<sup>13</sup>C ratios in stars of open clusters in order to better understand reasons of abundance alterations caused by stellar evolution. Information on abundances of heavier chemical elements will be used for deriving the time evolution of abundances in the Galactic disk under the Bologna Open Cluster Chemical Evolution (BOCCE) study (Bragaglia & Tosi 2006, Carretta et al. 2007, and references therein). In this work, our target of investigations is the open cluster IC 4651.

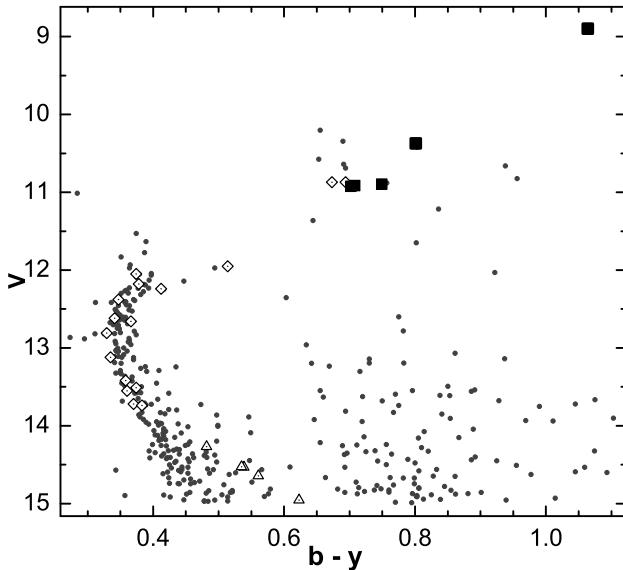
The open cluster IC 4651 is an intermediate-age (1.7 Gyr) open cluster located 140 pc below the Galactic plane and 7.1 kpc from the Galactic centre (Meibom et al. 2002; Pasquini et al. 2004). Meibom et al. (2002) provided calculations of the space motion and the Galactic orbit of the

cluster. The orbital eccentricity is  $e = 0.19$  and the mean radius of galactocentric orbit is 8.6 kpc, its maximum distance from the Galactic plane is 190 pc ( $\alpha_{2000} = 17^h 24.8^m$ ,  $\delta_{2000} = -49^\circ 56.0'$ ;  $l = 340.088^\circ$ ,  $b = -07.907^\circ$ ).

Results of extensive photometric studies were published first by Eggen (1971) and Lindoff (1972) and later on by Anthony-Twarog & Twarog (1987, 2000), Anthony-Twarog et al. (1988). However, the most recent photometric study was performed by Meibom (2000) and Meibom et al. (2002). They combined photometric observations and radial velocity measurements for the 44 single member stars down to  $V = 14.5$  mag and determined  $E(B - V) = 0.10$  mag, the distance  $d = 1.01 \pm 0.05$  kpc, and the mean radial velocity equal to  $-30.76 \pm 0.20$  km s<sup>-1</sup>. It was found that 37% of giant members are spectroscopic binaries with periods up to 5000 days, and 52% of the main-sequence and turn-off members are binaries with periods less than 1000 days. The estimated total mass of IC 4651 is  $\approx 630 M_\odot$  (Meibom et al. 2002). The turn-off mass of the IC 4651 stars  $M = 1.69 M_\odot$  was obtained by Carretta et al. (2004) reading the turn-off values on the Girardi et al. (2000) isochrones for solar metallicity at the age of the cluster of 1.7 Gyr as determined by Meibom et al. (2002).

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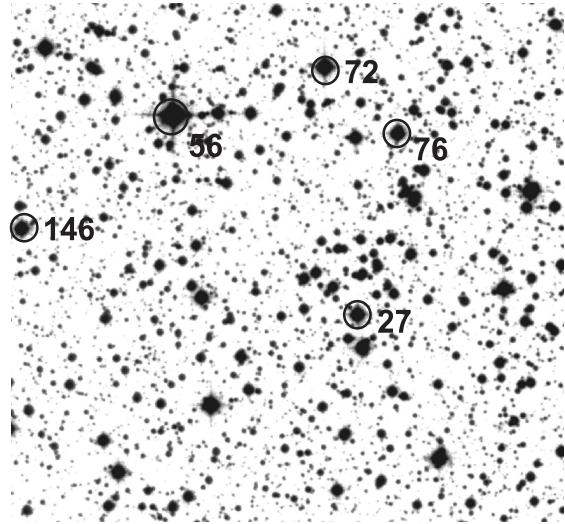
**Figure 1.** The colour-magnitude diagram of the open cluster IC 4651. The stars investigated in this work are indicated by the filled squares. The stars of two other high-resolution spectral abundance studies are shown in this plot as well: the work of Pace et al. (2008) is marked by triangles and of Pasquini et al. (2004) – by diamonds. The diagram is based on Strömgren photometry by Anthony-Twarog & Twarog (2000).

There were several photometric studies that evaluated the metallicity of IC 4651. Based on  $uvby - H_\beta$  photometry,  $[Fe/H] = 0.23 \pm 0.02$  was found by Anthony-Twarog & Twarog (1987),  $[Fe/H] = 0.18 \pm 0.05$  by Nissen (1988), and  $[Fe/H] = 0.077 \pm 0.012$  by Anthony-Twarog & Twarog (2000).

High resolution spectroscopic data started to appear in the beginning of the millennium. Bragaglia et al. (2001) determined the mean metallicity of five evolved stars  $[Fe/H] = 0.16 \pm 0.01$ . Pasquini et al. (2004) provided the cluster metallicity  $[Fe/H] = 0.10 \pm 0.03$  from the analysis of 22 faint main sequence stars of the cluster. Abundances of the iron peak,  $\alpha$ -elements and lithium were investigated in their study as well. Carretta et al. (2004) found the average  $[Fe/H] = 0.11 \pm 0.01$  for 5 evolved stars of the cluster, which we analyse further in this our work. Pace et al. (2008) provided the abundance measurements of Fe, Ca, Na, Ni, Ti, Al, Cr, Si for 20 solar-type stars belonging to IC 4651 and found  $[Fe/H] = 0.12 \pm 0.05$ . And finally, Santos et al. (2009) derived the mean metallicity  $[Fe/H] = 0.15 \pm 0.02$  for IC 4651 from five dwarf stars.

In our work for the open cluster IC 4651, the detailed abundance analysis of almost 30 chemical elements is done. Abundances of such key chemical elements as  $^{12}\text{C}$ ,  $^{13}\text{C}$ , N, O as well as representatives of s- and r-processes are determined.

The colour-magnitude diagramme of IC 4651 with the stars analysed in three most comprehensive chemical abundance studies (Pasquini et al. 2004; Pace et al. 2008 and this work) indicated is presented in Fig. 1.



**Figure 2.** Field of  $8 \times 8$  arcmin $^2$  centered on IC 4651, with the programme stars indicated by their numbers according to Lindoff (1972).

## 2 OBSERVATIONS AND METHOD OF ANALYSIS

The spectra of five cluster stars (IC 4651 27, 56, 72, 76 and 146) were obtained with the spectrograph FEROS (Fiber-fed Extended Range Optical Spectrograph) mounted at the 1.5 m telescope in La Silla (Chile). The resolving power is  $R = 48\,000$  and the wavelength range is  $\lambda\lambda 3700\text{--}8600 \text{\AA}$ . Three stars (27, 76, 146) belong to the red clump of the cluster, the IC 4651 72 star is a first-ascent giant, and the star 56 is an RGB-tip giant (see Fig. 1). The finding chart of the investigated stars is shown in Fig. 2. The log of observations and S/N are presented in the paper by Carretta et al. (2004).

In the same paper by Carretta et al. (2004), all the main atmospheric parameters for the observed stars were determined. For the convenience we present them in this paper as well (Table 1). The effective temperatures were derived by minimizing the slope of the abundances from neutral Fe I lines with respect to the excitation potential. Using the line-depth ratios (LDR) technique, Biazzo et al. (2007) have determined higher effective temperatures for other clump stars in NGC 4651 and have raised doubts that the temperature determinations by Carretta et al. were likely too low. We have checked dependences of the other chemical element lines with respect to the excitation potential and did not find slopes. Thus, we do not doubt in the correctness of effective temperature determinations for IC 4651 giants by Carretta et al.

The gravities ( $\log g$ ) were derived by Carretta et al. from the iron ionization equilibrium. In our study we found a very good agreement between neutral and singly ionised species of Cr and Ti, which strongly support the reliability of the atmospheric parameters, in particular the gravity values derived from the ionization equilibrium of Fe. The microturbulent velocities were determined assuming a relation between  $\log g$  and  $v_t$ . The ATLAS models with overshooting were used for the analysis. The Fe I lines were restricted to

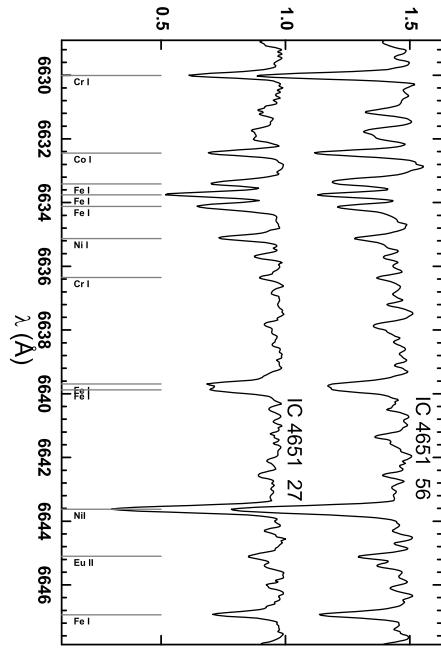


Figure 3. Small samples of stellar spectra of programme stars in IC 4651. An offset of 0.5 in relative flux is applied for clarity.

Table 1. Adopted atmospheric parameters for observed stars in IC 4651.

Star*	<i>V</i>	<i>B – V</i>	<i>T<sub>eff</sub></i> (mag)	<i>log g</i>	[A/H]	<i>v<sub>t</sub></i> (km s <sup>-1</sup> )
27	10.86	1.23	4610	2.52	0.10	1.17
56	8.95	1.68	3950	0.29	-0.34	1.46
72	10.41	1.33	4500	2.23	0.13	1.21
76	10.94	1.17	4620	2.26	0.11	1.21
146	10.94	1.14	4730	2.14	0.10	1.21

\* Star numbers, *V* and *B – V* from Lindoff (1972)

the spectral range 5500–7000 Å in order to minimize problems of line crowding and difficulties in the continuum tracing blue-ward. Two examples of spectra are presented in Fig. 3. For more details and error estimates, see Carretta et al.

In this work we used the same method of analysis as in Mikolaitis et al. (2010, Paper I). Here we will remind only some details.

For the C<sub>2</sub> determination we calculated the 5632 – 5636 Å interval to compare with observations of C<sub>2</sub> Swan 0 – 1 band head at 5630.5 Å. The interval 7980 – 8130 Å contains strong <sup>12</sup>C/<sup>14</sup>N and <sup>13</sup>C/<sup>14</sup>N features, so it was used for the nitrogen abundance and <sup>12</sup>C/<sup>13</sup>C ratio analysis. We derived the oxygen abundance from synthesis of the forbidden [O I] line at 6300 Å. The *gf* values for <sup>58</sup>Ni and <sup>60</sup>Ni isotopic line components, which blend the oxygen line, were taken from Johansson et al. (2003). In the spectra of IC 4651 stars the [O I] line was not contaminated by telluric lines.

The abundances of Na and Mg were determined with NLTE taken into account as described by Gratton et al. (1999). Abundances of sodium were determined from equivalent widths of the Na I lines at 5688.22 Å, 6154.23 Å and 6160.75 Å; magnesium from the Mg I lines at 4730.04 Å, 5711.09 Å, 6318.71 Å, 6319.24 Å; and aluminum from the Al I lines at 6696.03 Å, 6698.67 Å, 7835.30 Å and 7836.13 Å.

The determination of zirconium, yttrium, barium, lanthanum, cerium, neodymium and europium abundances were performed by spectral synthesis method. The zirco-

Table 2. Effects on derived abundances resulting from model changes for the star IC 4651 72. The table entries show the effects on the logarithmic abundances relative to hydrogen,  $\Delta[\text{A}/\text{H}]$ . Note that the effects on “relative” abundances, for example [A/Fe], are often considerably smaller than abundances relative to hydrogen, [A/H]

Species	$\Delta T_{\text{eff}}$	$\Delta \log g$	$\Delta v_t$
	+100 K	+0.3	+0.3 km s <sup>-1</sup>
C(C <sub>2</sub> )	-0.05	0.05	0.00
N(CN)	0.05	0.00	0.05
O([O I])	-0.05	-0.05	0.00
Na I	0.09	-0.05	-0.04
Mg I	0.03	0.00	-0.03
Al I	0.08	0.00	-0.03
Si I	-0.06	0.07	-0.02
Ca I	0.11	-0.04	-0.06
Sc II	-0.02	0.13	-0.05
Ti I	0.16	-0.02	-0.08
Ti II	-0.03	0.13	-0.06
V I	0.16	0.01	-0.09
Cr II	0.10	0.00	-0.06
Cr III	-0.09	0.14	-0.03
Mn I	0.08	-0.04	-0.06
Co I	0.02	0.05	-0.07
Ni I	0.00	0.07	-0.05
Cu I	0.02	0.03	-0.06
Zn I	-0.05	0.07	-0.07
Y II	0.16	-0.02	-0.14
Zr I	0.00	0.12	-0.07
Ba II	-0.03	0.14	-0.02
La II	0.03	0.08	-0.10
Ce II	0.02	0.12	-0.03
Nd II	0.01	0.13	-0.04
Eu II	0.03	0.13	-0.07
<sup>12</sup> C/ <sup>13</sup> C	-2	-2	1

**Table 3.** Abundances relative to hydrogen [El/H]. The quoted errors,  $\sigma$ , are the standard deviations in the mean value due to the line-to-line scatter within the species. The number of lines used is indicated by  $n$ . The last two columns give the mean [El/Fe] and standard deviations for the cluster stars 27, 72, 76 and 146.

Species	27			56			72			76			146			Mean	
	[El/H]	$\sigma$	$n$	[El/Fe]	$\sigma$												
C ( $\text{C}_2$ )	-0.15		1	-0.64		1	-0.12		2	-0.17		1	-0.15		1	-0.26	0.02
N ( $\text{CN}$ )	0.36	0.07	24	-0.09	0.11	18	0.35	0.07	24	0.30	0.06	24	0.27	0.09	23	0.21	0.04
O ( $[\text{O I}]$ )	0.05		1	-0.27		1	0.09		1	0.16		1	0.18		1	0.01	0.06
Na I	0.09	0.05	3	-0.25	0.02	3	0.10	0.04	3	0.10	0.05	3	0.07	0.04	3	-0.02	0.01
Mg I	0.05	0.07	4	-0.40	0.08	4	0.05	0.09	4	0.09	0.05	4	0.08	0.09	4	-0.04	0.03
Al I	0.11	0.05	4	-0.22	0.07	4	0.13	0.02	4	0.17	0.04	4	0.09	0.03	4	0.02	0.03
Si I	0.25	0.08	9	-0.35	0.09	6	0.25	0.10	8	0.20	0.07	9	0.21	0.09	9	0.12	0.03
Ca I	0.17	0.05	9	-0.28	0.08	6	0.13	0.09	10	0.17	0.09	8	0.17	0.10	8	0.05	0.04
Sc II	0.17	0.02	9	-0.50	0.05	9	0.14	0.06	8	0.15	0.06	9	0.18	0.05	9	0.05	0.03
Ti I	0.25	0.08	24	-0.20	0.07	9	0.23	0.09	24	0.18	0.08	26	0.21	0.10	28	0.11	0.03
Ti II	0.21	0.09	6	-0.30	0.09	8	0.19	0.07	7	0.23	0.09	11	0.14	0.09	11	0.08	0.04
V I	0.20	0.07	9	-0.58	0.02	9	0.17	0.09	5	0.25	0.05	9	0.27	0.04	9	0.11	0.05
Cr I	0.10	0.05	19	-0.51	0.06	11	0.08	0.09	25	0.10	0.09	24	0.10	0.09	24	-0.01	0.02
Cr II	0.05	0.04	6	-0.50	0.05	6	0.00	0.09	9	0.08	0.09	6	0.07	0.04	6	-0.06	0.05
Mn I	0.20	0.04	6	-0.47	0.01	6	0.21	0.05	5	0.15	0.01	6	0.18	0.06	6	0.07	0.03
Co I	0.25	0.07	8	-0.18	0.09	5	0.20	0.07	9	0.24	0.08	8	0.27	0.08	8	0.13	0.04
Ni I	0.17	0.08	34	-0.25	0.10	30	0.20	0.09	34	0.17	0.07	36	0.17	0.08	36	0.07	0.01
Cu I	0.05	0.06	3	-0.33	0.07	3	0.08	0.02	3	0.16	0.01	3	0.10	0.02	3	-0.01	0.05
Zn I	0.00	0.06	2	-0.28	0.02	2	0.10	0.09	2	0.07	0.07	2	0.07	0.08	2	-0.05	0.03
Y II	0.07	0.05	6	-0.25	0.03	6	0.10	0.04	6	0.04	0.01	6	0.14	0.04	6	-0.02	0.05
Zr I	0.03	0.08	2	-0.34	0.01	2	0.00	0.05	2	0.04	0.02	2	0.00	0.05	2	-0.09	0.03
Ba II	0.03	0.03	3	-0.29	0.04	2	0.08	0.07	3	0.05	0.05	3	0.05	0.05	3	-0.06	0.01
La II	0.18	0.02	2	-0.33	0.02	2	0.10	0.05	2	0.15	0.03	2	0.15	0.05	2	0.03	0.05
Ce II	0.22	0.08	2	-0.30	0.02	2	0.20	0.07	2	0.24	0.01	2	0.20	0.07	2	0.11	0.03
Nd II	0.27	0.08	3	-0.18	0.04	2	0.28	0.06	3	0.15	0.05	3	0.18	0.03	3	0.11	0.06
Eu II	0.14		1	-0.25		1	0.10		1	0.13		1	0.10		1	0.01	0.03
C/N	1.23			1.12			1.34			1.35			1.5			1.36	0.11
$^{12}\text{C}/^{13}\text{C}$	17			14			15			14			18			16	2

## 2.1 Estimation of uncertainties

The sources of uncertainty were described in detail in our Paper I.

The sensitivity of the abundance estimates to changes in the atmospheric parameters by the assumed errors ( $\pm 100$  K for  $T_{\text{eff}}$ ,  $\pm 0.3$  dex for  $\log g$  and  $\pm 0.3$  km s $^{-1}$  for  $v_t$ ) is illustrated for the star IC 4651 72 (Table 2). It is seen that possible parameter errors do not affect the abundances seriously; the element-to-iron ratios, which we use in our discussion, are even less sensitive. The sensitivity of iron abundances to stellar atmospheric parameters were described in Carretta et al. (2004).

The scatter of the deduced line abundances  $\sigma$ , presented in Table 3, gives an estimate of the uncertainty due to the random errors, e.g. in continuum placement and the line parameters (the mean value of  $\sigma$  is 0.06). Thus the uncertainties in the derived abundances that are the result of random errors amount to approximately this value.

Since abundances of C, N and O are bound together by the molecular equilibrium in the stellar atmosphere, we have also investigated how an error in one of them typically affects the abundance determination of another.  $\Delta[\text{O/H}] = 0.10$  causes  $\Delta[\text{C/H}] = 0.05$  and  $\Delta[\text{N/H}] = -0.10$ ,  $\Delta[\text{C/H}] = 0.10$  causes  $\Delta[\text{N/H}] = -0.15$  and  $\Delta[\text{O/H}] = 0.02$ ,  $\Delta[\text{N/H}] = 0.10$  has no effect on either the carbon or the oxygen abundances.

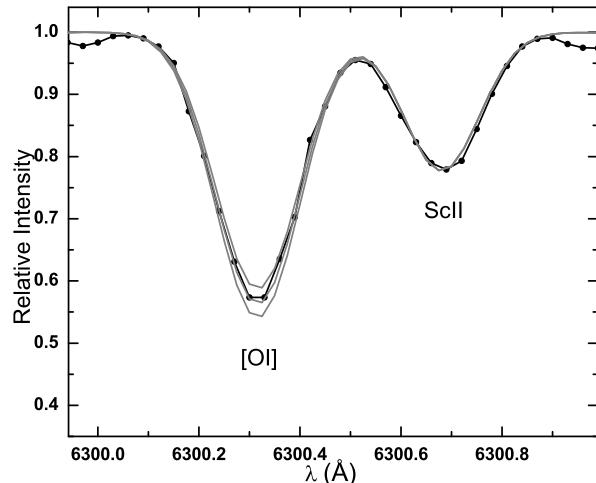
## 3 RESULTS AND DISCUSSION

The abundances relative to hydrogen [El/H]<sup>1</sup> and  $\sigma$  (the line-to-line scatter) derived for up to 27 neutral and ionized species (including  $^{13}\text{C}$ ) for the programme stars are listed in Table 3. The average cluster abundances [El/Fe] and dispersions about the mean values for IC 4651 are presented in Table 3 as well. They are calculated from the results determined for the stars 27, 72, 76 and 146. Due to the different [Fe/H], which is by 0.4 dex lower than of other cluster stars, the star 56 was not used in the average calculations even though its values do not change the average abundances much. For the majority of the chemical elements the changes are just  $\pm 0.01 - 0.02$  dex, only for Si I and Sc II the difference is 0.04 dex, and for V I – 0.07 dex. From its element to iron ratios, C/N and  $^{12}\text{C}/^{13}\text{C}$  ratios, this star within errors of uncertainties is indistinguishable from other evolved stars of this cluster. However, we think that with more adequate model atmospheres this star can be investigated more accurately. In Fig. 4 we show an example of spectrum syntheses for the [OI] line in IC 4651 56. In Fig. 3 a sample of its spectrum is shown as well.

In IC 4651, the majority of investigated chemical elements have abundance ratios close to the solar ones. The mean cluster  $[\alpha/\text{Fe}] \equiv \frac{1}{4}([\text{Mg}/\text{Fe}] + [\text{Si}/\text{Fe}] + [\text{Ca}/\text{Fe}] + [\text{Ti}/\text{Fe}]) = 0.06 \pm 0.07$  (s.d.), which is close to the solar value.

Abundances of Na I, Al I, Si I, Ca I, Ti I and Ni I were determined for the main-sequence stars of IC 4651 by Pace et al. (2008). The mean [El/Fe] ratios in these stars are very close to solar as well.

<sup>1</sup> In this paper we use the customary spectroscopic notation  $[\text{X}/\text{Y}] \equiv \log_{10}(N_{\text{X}}/N_{\text{Y}})_{\text{star}} - \log_{10}(N_{\text{X}}/N_{\text{Y}})_{\odot}$



**Figure 4.** Fit to the forbidden [OI] line at 6300 Å in IC 4651 56. The observed spectrum is shown as a solid line with black dots. Synthetic spectra with [O/Fe] = 0.3, 0.08, and 0.13 are shown as solid gray lines.

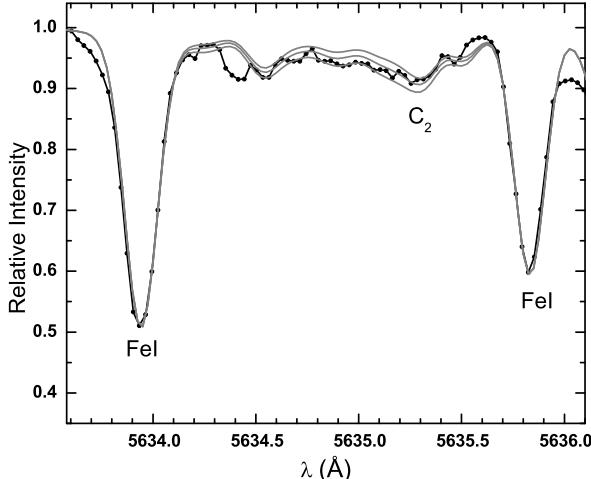
**Table 4.** The mean [El/Fe] for giant (G) and main-sequence (MS) stars of IC 4651 investigated in this work, Pasquini et al. (2004) and Pace et al. (2008).

Species	This work	Pasquini		Pace
	[El/Fe] G	[El/Fe] G	[El/Fe] MS	[El/Fe] MS
Na I	0.00	0.19	-0.09	-0.03
Mg I	-0.05	0.09	0.13	
Al I	0.03	0.07	-0.07	-0.10
Si I	0.09	0.08	0.07	-0.02
Ca I	0.05	0.00	0.04	0.04
Sc II	0.01	0.11	-0.11	
Ti I	0.11	0.12	0.08	-0.02
Ti II	0.07	0.18	0.00	
Cr I	-0.05	-0.02	0.11	
Ni I	0.07	0.10	0.01	-0.02

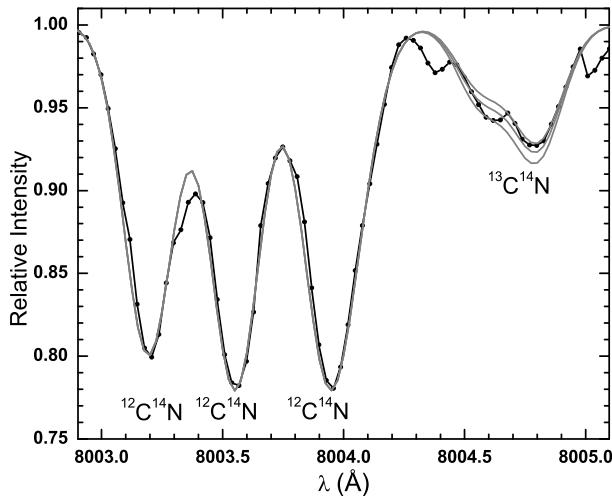
Pasquini et al. (2004) investigated spectra of both giants and main-sequence stars in IC 4651. The authors expressed their strong belief that [Na/Fe] ratio is comprehensively higher in the giants in comparison to the main-sequence stars and that this is due to internal nucleosynthesis and mixing. However, neither Pace et al. (2008), neither our study may confirm this statement. In Table 3, we present the mean [El/Fe] for giant and main-sequence stars of IC 4651 investigated in our work, Pasquini et al. (2004) and Pace et al. (2008). In our work, the abundances of Na and Mg were determined with NLTE taken into account, and we do not find an overabundance of these chemical elements.

In Fig. 4 of Paper I, we presented the radial distribution of some elemental abundances for BOCCE clusters analysed so far, and for others in recent studies. IC 4651 agrees well with results of other open clusters at the same  $R_{\text{gc}}$  of 7.1 kpc.

In the following sections we will discuss in more detail the results of carbon and nitrogen abundance determinations.



**Figure 5.** Small region of IC 4651 27 spectrum (solid black line with black dots) at C<sub>2</sub> Swan (0,1) band head 5635.5 Å, plotted together with synthetic spectra with [C/Fe] values lowered by  $-0.2$  dex (lower gray line),  $-0.25$  dex (middle gray line) and  $-0.3$  (upper gray line).



**Figure 6.** Small region of IC 4651 72 spectrum (solid black line with black dots) with <sup>13</sup>C<sup>14</sup>N feature. Grey lines show synthetic spectra with <sup>12</sup>C/<sup>13</sup>C ratios equal to 13 (lower line), 15 (middle line) and 17 (upper line).

### 3.1 Carbon and nitrogen abundances

The average value of carbon to iron ratio in IC 4651 is  $[C/Fe] = -0.27 \pm 0.02$ . In Fig. 5, a fit to the IC 4651 27 spectrum at C<sub>2</sub> 5635.5 Å is shown.

We compared the carbon abundance in IC 4651 with carbon abundances determined for dwarf stars in the Galactic disk. Shi et al. (2002) performed an abundance analysis of carbon for a sample of 90 F and G type main-sequence disk stars using C I and [C I] lines and found [C/Fe] to be about solar at the solar metallicity. Roughly solar carbon abundances were found by Gustafsson et al. (1999) who analysed a sample of 80 late F and early G type dwarfs using the forbidden [C I] line. The ratios of [C/Fe] in our stars lie about 0.3 dex below the values obtained for dwarf stars of the Galactic disk.

The mean nitrogen to iron abundance ratio in IC 4651 is  $[N/Fe] = 0.21 \pm 0.04$ . This shows that nitrogen is overabundant in these evolved stars of IC 4651, since [N/Fe] values in the Galactic main-sequence stars are about solar at the solar metallicity (c.f. Shi et al. 2002). Unfortunately, neither carbon, neither nitrogen abundances were investigated in the main sequence stars of IC 4651 by Pace et al. (2008) and Pasquini et al. (2004).

The mean C/N ratios in IC 4651 is equal to  $1.36 \pm 0.11$ . The smallest value of C/N = 1.12 was obtained for the star IC 4651 56.

The <sup>12</sup>C/<sup>13</sup>C ratios were determined for all programme stars from the (2,0) <sup>13</sup>C<sup>14</sup>N feature at 8004.728 Å. In Fig. 6 we show a small region of IC 4651 72 spectrum together with spectral syntheses obtained with three different values of the carbon isotopic ratio. We find that the mean <sup>12</sup>C/<sup>13</sup>C ratios are about  $16 \pm 2$  in the evolved stars investigated.

The solar carbon and nitrogen abundances used in our work are  $\log A_C = 8.52$  and  $\log A_N = 7.92$  (Grevesse & Sauval 2000), so the solar C/N = 3.98. The <sup>12</sup>C/<sup>13</sup>C ratio in the solar photosphere is equal to 89 (Coplen et al. 2002).

### 3.2 Comparison of <sup>12</sup>C/<sup>13</sup>C and C/N ratios with theoretical models

The carbon and nitrogen abundances, C/N and especially the carbon isotope ratios <sup>12</sup>C/<sup>13</sup>C are key tools for stellar evolution studies. Investigations of abundances of these chemical elements in atmospheres of clump stars of open clusters may provide a comprehensive information on chemical composition changes. The clump stars have accumulated all chemical composition changes that have happened during their evolution along the giant branch and during the helium flash.

In Fig. 7 and 8, we compare the mean carbon isotope and C/N ratios of clump stars in different open clusters as a function of turn-off mass with the theoretical models of the 1<sup>st</sup> dredge-up, thermohaline mixing (TH), thermohaline mixing together with rotation-induced mixing for stars at the zero age main sequence (ZAMS) having rotational velocities of  $110 \text{ km s}^{-1}$ ,  $250 \text{ km s}^{-1}$  and  $300 \text{ km s}^{-1}$  computed by Charbonnel & Lagarde (2010); and Cool Bottom Processing model (CBP) by Boothroyd & Sackman (1999).

The most recent modelling of extra-mixing processes was done by Charbonnel & Lagarde (2010). They are based on ideas of Eggleton et al. (2006) and Charbonnel & Zahn (2007). Eggleton et al. (2006) found a mean molecular weight ( $\mu$ ) inversion in their  $1M_\odot$  stellar evolution model, occurring after the so-called luminosity bump on the red giant branch, when the H-burning shell source enters the chemically homogeneous part of the envelope. The  $\mu$ -inversion is produced by the reaction <sup>3</sup>He(<sup>3</sup>He, 2p)<sup>4</sup>He, as predicted by Ulrich (1972). It does not occur earlier, because the magnitude of the  $\mu$ -inversion is small and negligible compared to a stabilizing  $\mu$ -stratification. Following Eggleton et al. (2006), Charbonnel & Zahn (2007) have computed stellar models including the prescription by Ulrich (1972) and extended them to the case of a non-perfect gas for the turbulent diffusivity produced by that instability in a stellar radiative zone. They found that a double diffusive instability referred to as thermohaline convection, which has been discussed long ago in

**Table 5.**  $^{12}\text{C}/^{13}\text{C}$  and C/N ratios along with turn-off mass, age, galactocentric distance and atmospheric parameters for clump stars

Cluster	Star	$M_{\text{TO}}(M_{\odot})$	Age(Gyr)	$R_{\text{gc}}(\text{kpc})$	$T_{\text{eff}}(\text{K})$	$\log g$	[A/H]	$^{12}\text{C}/^{13}\text{C}$	C/N	Ref.*
NGC 752	1	1.60	2.0	8.75	5000	2.85	0.1	16	–	1
	75				4900	2.85	0.1	13	–	1
	77				4900	2.85	0.2	16	–	1
	213				5000	2.90	0.1	14	–	1
	295				5000	2.90	0.2	15	–	1
NGC 2360	50	2.02	1.15	6.32	5015	2.90	-0.03	–	1.04	5
	62				5105	3.15	0.12	–	1.38	5
	86				4960	2.65	-0.06	–	0.93	5
	12				4800	2.70	0.2	14.5	–	1
NGC 2447	28	1.90	0.45	6.51	5060	2.70	-0.01	–	0.69	5
	34				5120	2.90	-0.01	–	0.87	5
NGC 2682	F84	1.20	5.0	9.05	4750	2.4	-0.02	20	1.15	3
	F141				4730	2.4	-0.01	16	1.32	3
	F151				4760	2.4	-0.03	17	1.32	3
	F164				4700	2.5	0.00	18	1.62	3
	F224				4710	2.4	-0.11	8	1.58	3
	F226				4730	2.4	-0.02	15	1.62	3
	F84				4800	2.70	0.0	11.5	–	1
	F141				4800	2.70	0.0	10.5	–	1
	F164				4800	2.70	0.0	10.5	–	1
NGC 2714	5	2.91	0.40	8.34	5070	2.70	0.12	–	0.83	5
NGC 3532	19	3.03	0.35	7.87	4995	2.65	0.11	12	1.02	5
	122				5045	2.60	-0.02	–	0.93	5
	596				5020	2.50	0.04	–	0.95	5
	HD95879				5000	2.25	0.08	10	1.10	2
NGC 5822	HD96174				5000	2.17	0.00	15	0.59	2
	HD96175				5100	2.25	0.12	15	0.44	2
	HD96445				5000	2.36	0.13	10	1.51	2
	201	2.19	0.9	8.10	5035	2.85	0.05	13	0.87	5
	316				5110	3.05	0.16	–	1.00	5
NGC 6134	39	2.34	0.7	7.6	4980	2.52	0.24	9	1.48	6
	69				4950	2.83	0.11	12	1.38	6
	75				5000	3.10	0.22	7	1.41	6
	114				4940	2.74	0.11	6	1.05	6
	129				5000	2.98	0.05	8	0.98	6
	157				5050	2.92	0.16	12	1.10	6
	30				4980	2.95	0.21	12	0.93	5
NGC 6281	3	3.18	0.3	8.47	4915	2.30	0.01	12	0.64	5
	4				5015	2.50	0.09	12	0.95	5
NGC 6633	100	2.79	0.45	8.42	5015	2.85	0.11	21	0.91	5
NGC 7789	K605	1.60	1.4	9.43	4860	2.4	-0.02	10	1.05	4
	K665				4970	2.4	0.00	9	1.45	4
	K732				4900	2.3	0.02	7	1.51	4
IC 2714	5	2.85	0.40	8.34	5070	2.70	0.12	–	0.83	5
IC 4651	27	1.69	1.7	7.1	4610	2.52	0.10	17	1.23	7
	76				4620	2.26	0.11	14	1.35	7
	146				4730	2.14	0.10	18	1.50	7
IC 4756	12	2.37	0.7	7.23	5030	2.75	-0.01	11	0.91	5
	14				4720	2.47	0.03	17	1.02	5
	38				5075	3.00	0.05	10	1.20	5
	69				5130	3.00	0.08	5	1.15	5
	144				5200	3.20	0.0	18	–	1
	176				5200	3.00	0.0	12	–	1
	228				5000	2.90	0.0	21	–	1
	296				5000	2.90	0.0	18	–	1

\* 1 – Gilroy (1989); 2 – Luck(1994); 3 – Tautvaišienė et al. (2000); 4 – Tautvaišienė et al. (2005); 5 – Smiljanic et al. (2009); 6 – Mikolaitis et al. (2010); 7 – This work.

the literature (Stern 1960), is important in evolution of red giants. This mixing connects the convective envelope with the external wing of hydrogen burning shell and induces surface abundance modifications in red giant stars.

Charbonnel & Lagarde (2010) also computed the models of rotation-induced mixing for stars at the zero age main sequence having rotational velocities of  $110 \text{ km s}^{-1}$ ,  $250 \text{ km s}^{-1}$  and  $300 \text{ km s}^{-1}$ . Typical initial ZAMS rotation velocities were chosen depending on the stellar mass based on observed rotation distributions in young open clusters (Gaigé 1993). The convective envelope was supposed to rotate as a solid body through the evolution. The transport coefficients for chemicals associated to thermohaline and rotation-induced mixings were simply added in the diffusion equation and the possible interactions between the two mechanisms were not considered. The rotation-induced mixing modifies the internal chemical structure of main sequence stars, although its signatures are revealed only later in the stellar evolution.

The models by Boothroyd & Sackmann (1999) include the deep circulation mixing below the base of the standard convective envelope, and the consequent "cool bottom processing" (CBP) of CNO isotopes.

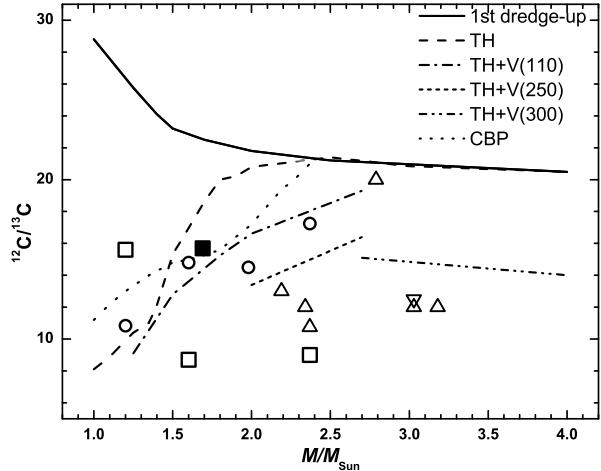
The theoretical models were compared to the observational data of  $^{12}\text{C}/^{13}\text{C}$  and C/N listed in Table 5, which we collected for clump stars of open clusters investigated by Mikolaitis et al. (2010), Smiljanic et al. (2009), Tautvaišienė et al. (2000, 2005), Luck (1994) and Gilroy (1989). From Gilroy (1989) we selected 4 clusters with well defined red clump stars. Luck (1994) derived carbon isotope ratios for 8 open clusters, however only one cluster was included to our comparison since for other clusters it was very difficult to identify stars of red clump. The turn-off masses, ages and galactocentric distances were chosen from the most recent studies and used for displaying of other  $^{12}\text{C}/^{13}\text{C}$  and C/N investigations for the same cluster, if available.

In Fig. 7 and 8 we can see that for clusters with stars of smaller turn-off masses the  $^{12}\text{C}/^{13}\text{C}$  and C/N values are in a good agreement with both models of extra-mixing used for the comparison. However,  $^{12}\text{C}/^{13}\text{C}$  values in the clump stars with turn-off masses of  $2\text{--}3 M_\odot$  in most of the investigated clusters are lower than predicted by the available models and need modelling of larger extra-mixing.

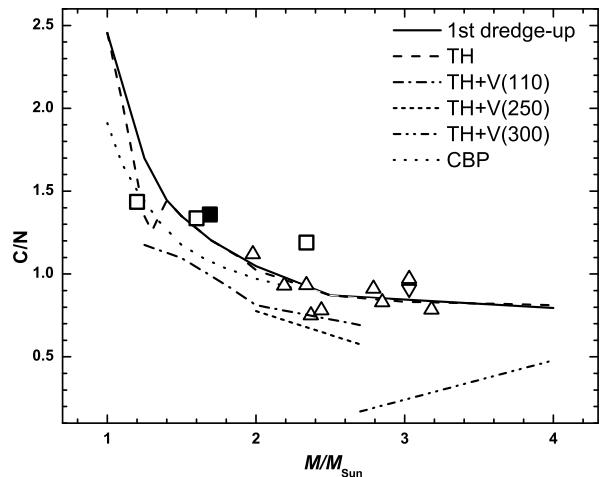
### 3.3 Final remarks

Carbon and nitrogen are important products of nucleosynthesis processes in stellar interiors, and the evidence of their abundance variation during stellar evolution is a signature of physical mixing processes between the atmosphere and deeper layers of a star. Such abundance alterations may be well traced in open clusters. They provide a unique possibility for investigation of a number of stars of nearly the same age, distance and origin, as open cluster stars are claimed to be formed in the same protocloud of gas and dust. Open clusters have a high reliability of mass, distance, evolutionary phase and abundance determinations.

Extra-mixing processes may become efficient on the red giant branch when stars reach the so-called RGB bump, and may modify the surface abundances. It is known that alterations of  $^{12}\text{C}/^{13}\text{C}$  and  $^{12}\text{C}/^{14}\text{N}$  ratios depend on stellar evolutionary stage, mass and metallicity (see Charbonnel et al.



**Figure 7.** The average carbon isotope ratios in clump stars of open clusters as a function of stellar turn-off mass. The result of this work is marked by the filled square; from Mikolaitis et al. (2010) and Tautvaišienė et al. (2000, 2005) – open squares; from Smiljanic et al. (2009) – open triangles; from Luck (1994) – reversed open triangle; from Gilroy (1989) – open circles. The models of the 1<sup>st</sup> dredge-up, thermohaline mixing (TH) and rotation-induced mixing (V) are taken from Charbonnel & Lagarde (2010). The CBP model of extra-mixing is taken from Boothroyd & Sackmann (1999).



**Figure 8.** The average carbon to nitrogen ratios in clump stars of open clusters as a function of stellar turn-off mass. The meaning of symbols are as in Fig. 7.

1998, Gratton et al. 2000, Chanamé et al. 2005, Cantiello & Langer 2010; Charbonnel & Lagarde 2010 for more discussion).

The comparison of the observational data with theoretical models of stellar evolution shows that processes of extra-mixing in stars of open clusters with turn-off masses of  $2\text{--}3 M_\odot$  are larger than predicted.

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